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## SIVERS ASYMMETRY IN $e + p^\uparrow \rightarrow e + J/\psi + X$

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A recent investigation of the single spin asymmetry (SSA) in low virtuality electroproduction/photoproduction of  $J/\psi$  in color evaporation model is presented. It is shown that the asymmetry is sizable and can be used as a probe for the still unknown gluon Sivers function.

*Keywords:* single spin asymmetry, Sivers function, TMD

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### 1. Introduction

Large single spin asymmetries (SSA) observed when an unpolarized beam of electrons or protons is scattered off a transversely polarized target can be explained with the inclusion of  $\mathbf{k}_\perp$  dependence in parton distribution functions (pdf's) and fragmentation functions (ff's) <sup>1</sup>. In recent years, there has been a lot of interest in investigations of transverse single spin asymmetries in high energy QCD processes as they provide information about spin and orbital angular momentum carried by the quarks and gluons. Large SSA's have been measured in pion production at Fermilab <sup>2</sup> as well as at BNL-RHIC in  $pp^\uparrow$  collisions <sup>3</sup>. SSA's have also been observed by HERMES <sup>4</sup> and COMPASS <sup>5</sup> collaborations, in polarized semi-inclusive deep inelastic scattering. The magnitude of the observed asymmetries have been found to be larger than what is expected from perturbative QCD <sup>6</sup>. It is possible to explain this large asymmetry in terms of transverse momentum dependent (TMD) parton distribution functions. One is led to a generalized factorization formula called TMD factorization <sup>7,8</sup>, which in some processes has been proved at leading twist and leading order <sup>9</sup> and has been argued to hold at all orders. One of the TMD functions is the Sivers function which describes the probability of finding an unpolarized parton inside a transversely polarized hadron. Here, we propose charmonium production as a probe to investigate the Sivers function and estimate SSA in photoproduction (low virtuality electroproduction) of charmonium in scattering of electrons off transversely polarized protons. At leading order (LO), this receives contribution only from a single partonic subprocess  $\gamma g \rightarrow c\bar{c}$ . Hence, SSA in  $e + p^\uparrow \rightarrow e + J/\psi + X$ , if observed, can be used as a clean probe of gluon Sivers function. In addition, charmonium production mechanism can also have implica-

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tions for this SSA and therefore, its study can help to understand the production mechanism for charmonium.

## 2. Sivers Asymmetry in $J/\psi$ Production : Formulas

There are several models for charmonium production. In the color singlet model<sup>10</sup> the cross section for charmonium production is factorized into a short distance part for  $c\bar{c}$  pair production calculable in perturbation theory and a non-perturbative matrix element for the formation of a bound state, which is produced in a color singlet state. A more recent model of charmonium production is the color octet model<sup>11</sup>. This is based on a factorization approach in non-relativistic QCD (NRQCD) and it allows  $c\bar{c}$  pairs to be produced in color octet states. Here again, one requires knowledge of the nonperturbative colour octet matrix elements, which are determined through fits to the data on charmonium production. On the other hand, in color evaporation model (CEM), which we use in this work,<sup>12,13</sup> a statistical treatment of color is made and the probability of finding a specific quarkonium state is assumed to be independent of the color of heavy quark pair. We have used Weizsacker-Williams (WW) equivalent photon approximation for the photon distribution of the electron<sup>15,16</sup>, to calculate the cross section for the process  $e + p^\uparrow \rightarrow e + J/\psi + X$  at low virtuality of the photon. The underlying partonic process at LO is  $\gamma g \rightarrow c\bar{c}$  and therefore, the only  $k_\perp$  dependent pdf appearing is the gluon Sivers function. For a complete calculation of photoproduction of  $J/\psi$  one has to consider higher order contributions and also the resolved photon contributions<sup>14</sup>. Also the gauge links or Wilson lines present in the TMD distributions are important at higher order<sup>17</sup>.

According to CEM, the cross section for charmonium production is proportional to the rate of production of  $c\bar{c}$  pair integrated over the mass range  $2m_c$  to  $2m_D$

$$\sigma = \frac{1}{9} \int_{2m_c}^{2m_D} dM \frac{d\sigma_{c\bar{c}}}{dM} \quad (1)$$

where  $m_c$  is the charm quark mass and  $2m_D$  is the  $D\bar{D}$  threshold,  $M^2$  is the squared invariant mass of the  $c\bar{c}$  pair. The WW distribution function of the photon in the electron given by<sup>18</sup>,

$$f_{\gamma/e}(r, E) = \frac{\alpha}{\pi} \left\{ \frac{1 + (1-r)^2}{r} \left( \ln \frac{E}{m} - \frac{1}{2} \right) + \frac{r}{2} \left[ \ln \left( \frac{2}{r} - 2 \right) + 1 \right] + \frac{(2-r)^2}{2r} \ln \left( \frac{2-2r}{2-r} \right) \right\}. \quad (2)$$

where  $r$  is the energy fraction of the electron carried by the photon.

The single spin asymmetry for semi-inclusive process  $A^\uparrow + B \rightarrow C + X$  is defined as

$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \quad (3)$$

We assume a generalization of CEM expression by taking into account the transverse momentum dependence of the Weizsacker-Williams (WW) function and gluon

distribution function. The numerator of the SSA can be written as

$$\frac{d^4\sigma^\uparrow}{dydM^2d^2\mathbf{q}_T} - \frac{d^4\sigma^\downarrow}{dydM^2d^2\mathbf{q}_T} = \frac{1}{s} \int [d^2\mathbf{k}_{\perp\gamma} d^2\mathbf{k}_{\perp g}] \Delta^N f_{g/p^\uparrow}(x_g, \mathbf{k}_{\perp g}) f_{\gamma/e}(x_\gamma, \mathbf{k}_{\perp\gamma}) \times \delta^2(\mathbf{k}_{\perp\gamma} + \mathbf{k}_{\perp g} - \mathbf{q}_T) \hat{\sigma}_0^{\gamma g \rightarrow c\bar{c}}(M^2) \quad (4)$$

where  $y$  is the rapidity and  $q_T$  in the transverse momentum of the charmonium;  $\Delta^N f_{g/p^\uparrow}(x_g, \mathbf{k}_{\perp g})$  is the gluon Sivers function,  $f_{\gamma/e}(x_\gamma, \mathbf{k}_{\perp\gamma})$  is the photon distribution of the electron, given in the WW approximation. The denominator would have a similar expression involving the unpolarized gluon distribution of the proton;  $f_{g/p}(x_g, \mathbf{k}_{\perp g})$ , for which we use a gaussian form of  $k_\perp$  distribution and a similar gaussian form for the transverse momentum dependence of the WW function. To extract the asymmetry produced by the Sivers function, we calculate the weighted asymmetry<sup>19</sup>

$$A_N^{\sin(\phi_{q_T} - \phi_S)} = \frac{\int d\phi_{q_T} [d\sigma^\uparrow - d\sigma^\downarrow] \sin(\phi_{q_T} - \phi_S)}{\int d\phi_{q_T} [d\sigma^\uparrow + d\sigma^\downarrow]} \quad (5)$$

where  $\phi_{q_T}$  and  $\phi_S$  are the azimuthal angles of the  $J/\psi$  and proton spin respectively. For the gluon Sivers function we have used a model in our analysis, which has been used in the literature to calculate SSA in semi-inclusive deep inelastic scattering (SIDIS)<sup>20</sup> and Drell-Yan (DY) process<sup>21</sup> (see<sup>22</sup> for details). The parameters are taken from<sup>23</sup>. Other parameters we use are

$$\langle k_{\perp g}^2 \rangle = \langle k_{\perp\gamma}^2 \rangle = 0.25 \text{ GeV}^2.$$

### 3. Numerical results

In this section, we present numerical estimates of the Sivers asymmetry in charmonium production in different experiments. Model I refers to the parametrization in<sup>21</sup> and (a) refers to the parametrization of the gluon Sivers function in terms of an average of the u and d quark Sivers function<sup>22</sup>. The estimates are obtained using GRV98LO for gluon distribution functions. We point out that the scale evolution of the TMD's including the Sivers function has been worked out in<sup>24,25</sup> and recently it has been noted in<sup>26</sup> that in SIDIS the evolution indeed affects the Sivers asymmetry. However, in the model we consider for charmonium production, namely the color evaporation model, the only relevant scale is  $M^2$  which is the invariant mass of the heavy quark pair. This is integrated between a narrow region, from  $4m_c^2$  to  $4m_D^2$  irrespective of the center-of-mass energy of the experiment. So the scale evolution of the TMDs is not expected to affect the asymmetry too much.

In Figs. 1 and 2 we have shown the asymmetry ( $A_N^{\sin(\phi_{q_T} - \phi_S)}$ ) as a function of rapidity  $y$  and  $q_T$  respectively for COMPASS ( $\sqrt{s} = 17.33$  GeV) and eRHIC ( $\sqrt{s} = 31.6$  GeV) energies. The plots are for model I (a) and (b) for two choices of the gluon Sivers function. We obtain sizable asymmetry in the kinematical regions of all the experiments for model I (b). The asymmetry is smaller in model I (a). For COMPASS as well as for eRHIC the asymmetry increases with  $y$ , reaches a

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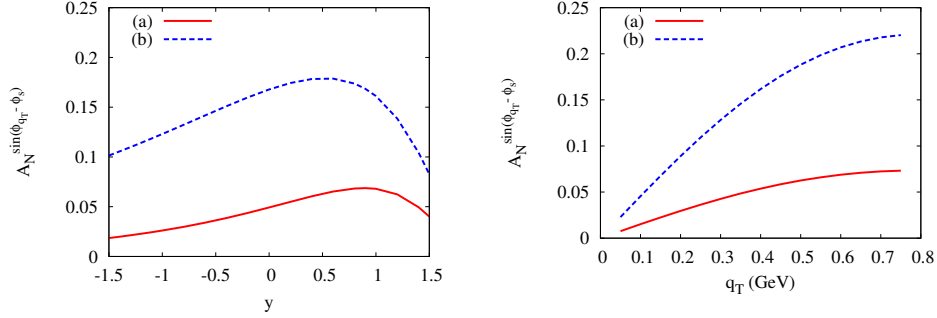


Fig. 1. The single spin asymmetry  $A_N^{\sin(\phi_{q_T} - \phi_S)}$  for the  $e + p^+ \rightarrow e + J/\psi + X$  at COMPASS as a function of  $y$  (left panel) and  $q_T$  (right panel). The plots are for model I with two parameterizations (a) (solid line) and (b) (dashed line). The integration ranges are  $(0 \leq q_T \leq 1)$  GeV and  $(0 \leq y \leq 1)$ . The results are given at  $\sqrt{s} = 17.33$  GeV.

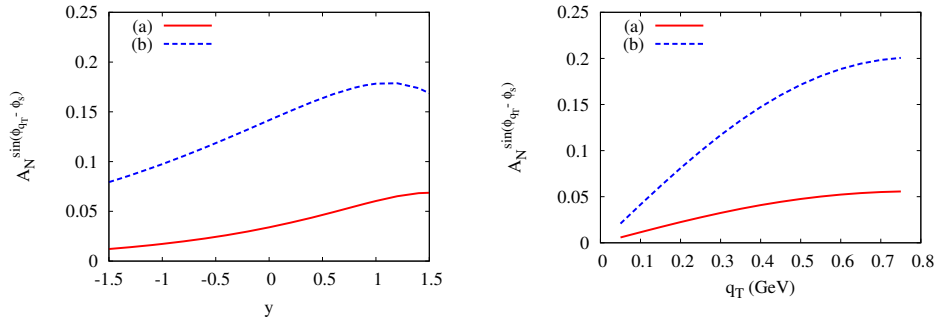


Fig. 2. The single spin asymmetry  $A_N^{\sin(\phi_{q_T} - \phi_S)}$  for the  $e + p^+ \rightarrow e + J/\psi + X$  at eRHIC as a function of  $y$  (left panel) and  $q_T$  (right panel). The plots are for model I with two parameterizations (a) (solid line) and (b) (dashed line). The integration ranges are  $(0 \leq q_T \leq 1)$  GeV and  $(0 \leq y \leq 1)$ . The results are given at  $\sqrt{s} = 31.6$  GeV.

maximum and then decreases. This maximum is reached at  $y \approx 0.6$  for COMPASS and at  $y \approx 1.2$  for eRHIC for model I (b). The asymmetry increases with  $q_T$  for both models, and for higher values of  $q_T \approx 0.6 - 0.7$  GeV, it becomes relatively steady.

In Fig. 3 we have shown a comparison of the  $y$  and  $q_T$  dependence of the asymmetry at different experiments, namely at JLab, HERMES, COMPASS and eRHIC. Different experiments cover different kinematical regions, and the plots clearly show that the asymmetry is sizable, and that SSA's in charmonium production is a useful tool to extract information on the gluon Sivers function.

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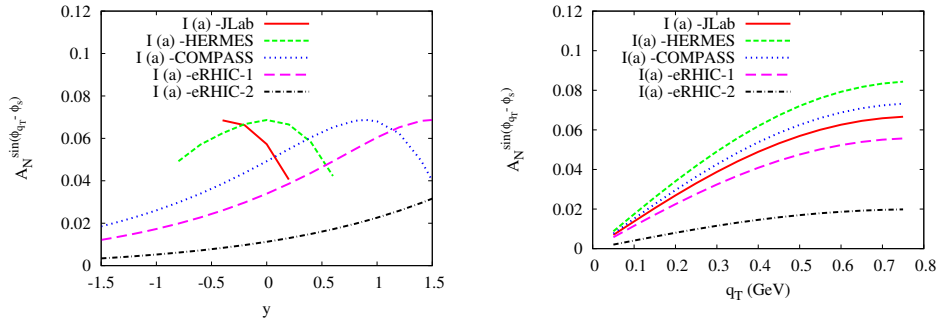


Fig. 3. The single spin asymmetry  $A_N^{\sin(\phi_{qT} - \phi_\psi)}$  for the  $e + p^\uparrow \rightarrow e + J/\psi + X$  as a function of  $y$  (left panel) and  $q_T$  (right panel). The plots are for model I with parameterization (a) compared for JLab ( $\sqrt{s} = 4.7$  GeV) (solid line), HERMES ( $\sqrt{s} = 7.2$  GeV) (dashed line), COMPASS ( $\sqrt{s} = 17.33$  GeV) (dotted line), eRHIC-1 ( $\sqrt{s} = 31.6$  GeV) (long dashed line) and eRHIC-2 ( $\sqrt{s} = 158.1$  GeV) (dot-dashed black line).

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